

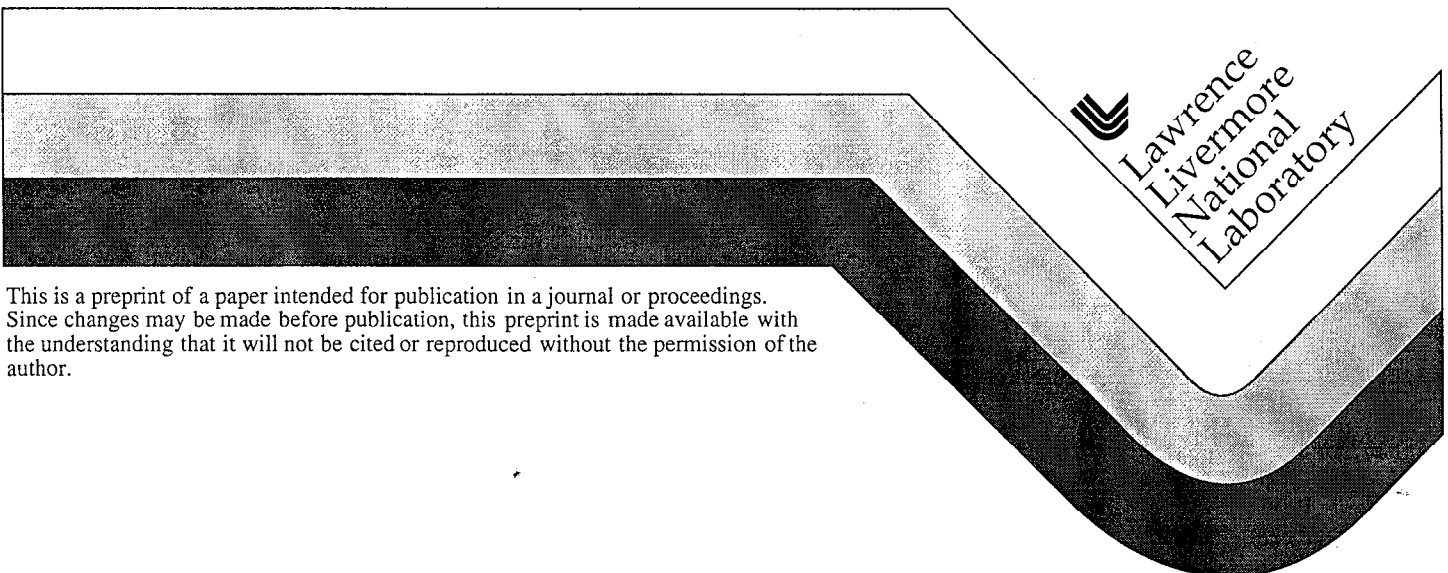
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Geolocation and route attribution in illicit trafficking of nuclear materials

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Nuclear forensic analysis is the process by which intercepted illicit nuclear materials and their associated materials, such as containers, are analyzed to provide clues to attribution. The goal of nuclear forensic analysis is to identify attribution indicators in an interdicted nuclear materials sample or its surrounding environment, e.g., container or transport vehicle. These indicators arise from known relationships between material characteristics and illicit activity. Thus, nuclear forensic analysis is more than the characterization of the material, which is simply a determination of the physical nature of the sample. It is convenient to categorize attribution into source and route attribution, and this report deals with route attribution. However, it is important to note that a number of important questions will draw upon both source and route attribution, e.g., identifying the point of loss of control of the nuclear materials.

Analyses of the nuclear materials themselves are expected to provide information that is most directly related to the source of the materials (i.e., production methods and processes). Analyses of the associated materials (e.g., packaging, containers and transportation vehicles) are expected to be more closely linked to the illicit route. Note that the questions that may be asked by the decision-making communities can also be related to the source and route as listed below.

Source Attribution Questions

1. Where did materials originate?
2. What are the materials - SNM, weapons grade, etc.?
3. Were materials diverted from a legitimate path?
4. Where were the materials obtained?
5. Where was legitimate custody lost?
6. What is the potential for more materials from this source?

Route Attribution Questions

1. Are the characteristics of the route unique?
2. What is the route the interdicted materials took?
3. Is this an isolated event or series of shipments?
4. Who are the participants in the smuggling operation?
5. What is the potential end use - e.g., Nation state weapons program, sub-national terrorist group, organized crime, etc.?

Forensic analysis alone can not answer all of these questions. Rather, the most complete answer requires that the results of forensic analyses be integrated with knowledge of radiochemical and environmental signatures, a

broad understanding of nuclear materials and weapons production, intelligence, and all other available information. This ensemble of information must be interpreted from several perspectives to obtain the most consistent and meaningful "attribution assessment". Attribution assessment is the integration of all relevant forms of information about a nuclear smuggling incident (which includes nuclear forensics plus information from all other sources) into a consistent and meaningful view. This assessment forms the basis of a confident response to the incident. The goal of attribution assessment is to answer policy makers' needs, requirements, and questions in their time framework for a given incident.

The forensic process begins with the detection of the incident and an on-site evaluation. The importance of on-site evaluations, field analyses, and proper sample collection cannot be overstated. Given the suspected presence of nuclear materials, it is essential that nuclear safety and security be given first priority at the recovery site.. Forensic activity in the presence of nuclear materials requires a unique capability to handle potentially large quantities of nuclear materials, while preserving trace quantities of non-nuclear materials with high potential forensic value. Critical information linking the source and route of the illicit materials with the responsible parties may be lost at this point if the collection opportunity is not fully exploited. The forensic analysis of evidence collected at a crime-scene is the only source of direct information to the attribution assessment. As in criminal forensic investigations, the identity of the critical piece of evidence leading to source and route determination is not known beforehand but must be developed during the course of the investigation. Prescreening and general examination of materials collected from illicit nuclear materials transaction scene are, therefore, critical steps in the forensic analysis. In order to obtain the maximum amount of forensic information, nuclear forensics experts should be called to participate at the site evaluation, whenever feasible.

After the sample is properly collected and packaged, it should be sent to a receiving location at an appropriate facility that can satisfy the requirements for both nuclear safety and preservation of forensic evidence. Prescreening by experts will be used by the nuclear forensics team to determine the course of further analyses, if any. If further analysis is deemed necessary, portions of the sample and its associated materials (such as containers) will be sent to appropriate technical experts. After analysis the technical results will be made available to the entire nuclear forensics team for interpretation.

The evaluation of the analytical techniques used to conduct forensic analyses for illicit trafficking of nuclear materials should be done in the context of the questions presented by the decision-makers. In other words, the value of a particular technique should be related to its utility to answer the various attribution questions. The task of providing decision makers with a timely and accurate assessment of an illicit nuclear materials incident requires that

the general approach be flexible. Utilizing a forensic approach under the direction of an appropriate team of experts provides the necessary flexibility. The team must be prepared to make use of whatever material or information becomes available. Therefore, an incident-specific analytical procedure should be used rather than a proscribed, comprehensive one. A proscribed approach would not provide a cost-effective or timely response to critical decision-maker questions.

In order to emphasize the incident specific nature of nuclear forensics, we identify here a set of "forensic tools" that could be used for route attribution. The ensemble of techniques that may initially be applied in a specific case may be viewed as a basic toolkit. As experience is gained, the toolbox may then be expanded. A forensic tool is categorized in terms of a particular analytical measurement on a particular type of material; the data provided through the application of the tool can be interpreted in the context of other information to help answer attribution questions.

The first aspect of a forensic tool is the type of material to which the tool can be applied. The broad categories of materials in forensic investigations are biological, geological, industrial materials, and packaging materials. The biological category includes microscopic entities (pollen, spores), vegetation, and animal and human materials. The geological category includes aerosols, soil, and rock fragments. Industrial materials can be subdivided into fluids and particles, and include all possible indicators of various industrial processes and materials. In this category we include such diverse elements as lubricants, explosive residues, industrial plant effluents, detritus from commercial products, etc. Finally, we include packaging materials.. This category includes bulk packaging materials, both the exterior container and all the non-nuclear materials contained therein, as well as particles and fibers adhering to the packaging materials.

The second aspect of a forensic tool is the type of analytical measurement that would be done on these materials. Our primary categories of analyses are isotopes, major and trace element compositions, organics, DNA, and physical/structural characteristics. The degree to which these various categories are utilized will vary according to the specifics of a particular case. The category of physical/structural characteristics includes any characterization that would identify the nature of the material that has been collected. For example, a physical/structural characterization of microscopic materials would help identify the types of vegetation and animal detritus that are present. It also includes specific, non-chemical characteristics of the collected material that would constrain the origin; fiber analysis is a well-known law enforcement example. It is important to emphasize that the tools categorized here include the traditional forensic tools that have been developed and used extensively by law enforcement.

Using this scheme of categorization, we present a matrix of forensic tools, shown in the next section on prioritization. Even using these very broad categories, there are 60 possible forensic tools. If the specifics of the types of materials and analytical techniques are included, the number becomes vastly greater. Accordingly, some type of prioritization and discretion should be utilized to select the most useful tools. This topic is addressed in the next section.

Prioritization of forensics tools

Presently, there are relatively few known cases of intercepted illicit nuclear materials, and fewer cases still in which many of the possible route forensic tools have been applied. Accordingly, past experience provides little guidance as to which route forensic tools will be most useful. Of course, the vast experience in criminal forensics will be extremely valuable for evaluating the nuclear forensics applications of traditional law-enforcement forensic tools. The relative merit assigned to these criminal forensic techniques compared to more novel approaches, e.g., isotopic measurements on geologic and industrial materials, however, is little more than an educated guess at this point. It is again important to emphasize that the value of these forensic tools depends upon a consideration of which scenarios are considered most likely and most important. The implementation of any of the nuclear forensic tools will be highly dependent on the policy makers' questions for a specific incident. Moreover, the ability to use a particular forensic tool in a specific case requires that the material is actually present and effectively collected.

The possible forensic tools are shown in Table 1. We present four categories of prioritization: essential, important, specialized, and not relevant. Essential forensic tools are those which could be applied in numerous cases, would answer the largest number of policy makers' questions, and provide timely answers. Essential tools are those which one would expect to be applied during the first round of forensic analyses. Specialized tools provide specific information but are not able to provide timely answers. Important tools fall in between the prior two categories. Important forensic tools may be extremely important for answering questions of route attribution, but they should be utilized after the initial set of essential forensic analyses are completed. Specialized tools are projected to be less useful across a broad set of scenarios, but it should be noted that in some cases these specialized tools might be of great importance, if highly unusual materials are present. The criminal forensic field abounds with examples in which material initially deemed to be incidental proves to be pivotal in the eventual successful conclusion of a case.

Table 1. Route Forensics Toolbox

	Isotopes	Major Elemental Composition	Trace Elemental Composition	Organic	DNA	F Ch
Biological:						
Pollen, spores			S		S	
Vegetation	S	S	S	S	S	
Animal/human	I	S	S	S	E	
Geological:						
Aerosols	S	I	S	S		
Soils	S	I	S	I		
Rock fragments	I	S	S			
Industrial Samples:						
Fluids	S	E	S	E		
Particles	I	E	S	I		
Packaging Materials:						
Bulk	S	S	S	S		
Particle/fiber	I	S	I	S		

E: essential

I: important

S: specialized

Blank: not relevant

Our strawman prioritization identifies 11 of 60 possible forensic tools as "essential", 9 as "important", 29 as "specialized", and the remainder (11) as not important. A future activity of the ITWG should be to evaluate this tentative prioritization based on actual case experience, designed exercises, and future research and development activities for some of the suggested route forensic tools.

It is important to recognize that no single measurement is ever likely to provide a unique geolocation that is very specific. However, in many cases the evidence provided by a suite of measurements can be interpreted to provide very strong constraints. One way of viewing the interpretational approach is to use each geolocation forensic measurement successively to narrow down the possible areas in the world that are consistent with the measurement. The final solution will be the area of overlap between all the geolocation indicators. Even if each indicator is still individually consistent with a substantial part of the earth, the intersection between just several indicators can often define a very small regional area.

Analytical Techniques for Route Forensics

The instruments listed here represent a proposed set that could be used in route forensics, but we emphasize that the actual selection of instrumental measurements will depend upon the specifics of the case. Moreover, the actual materials present (biological, geological, industrial, and packaging) will determine which techniques should be used. We list here a set of techniques which have been used in forensic applications. The list does not distinguish applications as a function of material type, nor was any attempt made to prioritize the various analytical techniques, e.g., to indicate which isotopic measurement is most important. We also list a brief description of the type of material best suited to each technique.

Isotopes

- Alpha spectrometry:
residual actinides
- Beta spectrometry:
fission and activation products
- Gamma spectrometry:
fission and activation products
- Secondary ion microprobe mass spectrometry:
in situ microanalysis, particles, H through Pu
- Thermal-ionization mass spectrometry:
metals, actinides
- Noble gas mass spectrometry:
low-level tritium, geologic age-dating
- Inductively-coupled plasma mass spectrometry:
rapid isotopic analyses

- Stable isotope mass spectrometry:
H, C, N, O, & S
- Accelerator mass spectrometry
cosmogenic radionuclides

Elemental Composition/Major & Trace

- ICP-MS:
Li through Pu, isotope-dilution option
- Inductively-coupled plasma optical emission spectroscopy:
generally less sensitive than ICP-MS
- X-ray fluorescence spectroscopy:
Ca through Pu, nondestructive
- Atomic absorption spectroscopy:
Li through U
- Scanning electron microscopy with X-ray analysis (SEM/EDS):
C through Pu, sub-micron-scale imaging, >0.05% abundances
- Secondary ion microprobe mass spectrometry (SIMS):
in situ microanalysis, particles, H through Pu, ppb sensitivity
- Particle-Induced X-ray Emission (PIXE):
Ca through U,
- Chemical separation techniques:
HPLC, ion-exchange, IC, TLC, CE
- Electron spectroscopy for chemical analysis (ESCA)
chemical speciation,

Organic

- Gas chromatography-mass spectrometry:
organic and organometallic compounds, 1-1000 amu
- Ion-trap mass spectrometry with MS-MS (ITMS):
GC-ITMS with thermal energy analyzer:
nitrogen-specific organic compounds
- Triple-quadrupole mass spectrometry:
ranges up to 500,000 amu

DNA

- Polymerase chain reaction (PCR):
DNA amplification
- DNA sequencing
- Electrophoresis
- Immunoassay

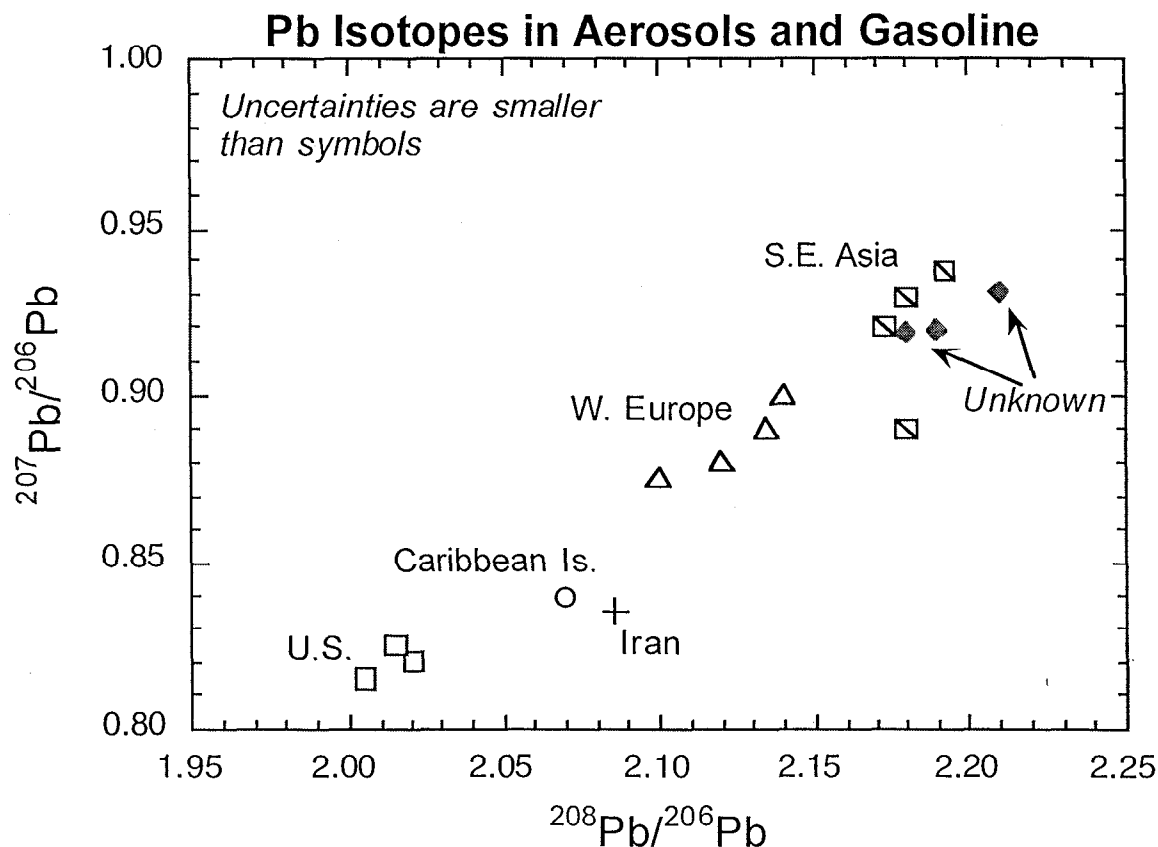
Physical & Structural Characteristics

- Optical Microscopy
- Scanning electron microscopy
- Transmission electron microscopy
- X-ray diffractometry (XRD)
- Radiography techniques

- Metallurgical techniques
- Biological techniques
- Molecular structure
FTIR, Raman, NMR

Examples of geolocation and route attribution applications

The stable isotopes of Pb provide a powerful isotopic fingerprint because common industrial lead sources generally have distinct isotopic compositions that can be traced back to the parental lead ore. In addition, Pb is often associated with the handling of special nuclear materials, providing the opportunity to use Pb isotope analysis to provide some clues about the location of previous handling and storage of the SNM. In the figure below for aerosols and gasolines, we see a distinct difference in isotopic compositions for continental regions. For the unknown sample of paper, we were asked to constrain the location where the paper was made. We developed a procedure for extracting Pb that was trapped within the paper when it was made. The isotopic composition of this lead is consistent with an origin in S. E. Asia, and rules out an origin in Western Europe and the U.S.



Another example, taken from the literature, is a study by Connan et al. in which they demonstrate the location specific isotope compositions of hydrogen and carbon for asphalts from four Middle East countries. Even for

these neighboring countries, the asphalts define four distinct, non-overlapping areas in a plot of D/H vs. C-13/C-12 ratios. The differences in isotopic composition are the result of interrelated chemical and biodegradation processes, which are themselves, location-specific. Weathering, for example, leads to changes in the relative abundances of the constituent organic molecules and significant shifts in D/H.

Non-nuclear materials adhering or incorporated into the surfaces of nuclear materials may provide valuable clues to the post-production handling of the nuclear materials. Oxygen and hydrogen isotopes may provide clues to the location at which surface oxide layers formed, since the isotopic composition of water vapor in the atmosphere has a well-known variability according to geographic location. The oxygen isotopes in the oxides of nuclear materials may also be useful for delineating their origins. The usefulness of this geolocation indicator depends upon the identity of the original source of the oxygen in the nuclear material, the degree to which the oxygen isotopic compositions in nuclear materials vary according to production location and the rate at which oxygen isotopes in surficial oxide layers exchange with the environment. Another class of potential clues might be provided by adhering contaminants or "contact" contaminants that are incorporated into the very near surface of the SNM itself. This is a relatively unexplored area with a number of key R&D needs: (a) establish typical environmental blanks for the measured analytes, (b) determine the extent to which particles and contaminants are present on typical nuclear materials, and (c) determine what evidence might be exploited for identifying storage locations.

Reference data for enhanced interpretation

The best interpretation of the results from the various forensic measurements can be obtained when specific knowledge exists of the range of possible results and all the reasonable sources have been identified and analyzed. Numerous data sets already exist, but in many cases the reference data for route attribution and geolocation are either quite general or not available. Nonetheless, even general conclusions can be very useful in a particular case because they can be used for identifying possible avenues to pursue that may give more specific information. For example, a geologic sample may constrain the possible sources of the sample sufficiently, especially when combined with other information from the case, that new reference data could be generated for the most likely sources. This approach is, of course, the most cost-effective, although it will not be as timely as in cases where existing databases are sufficient.

Another item for consideration is to develop the means for sharing existing data sets. Much of the basic data required for geolocation analysis is unclassified information available in the open literature. In cases where the specific data is considered proprietary, it would still be useful to share the interpretations that have been drawn by experts that have access to a

particular data set. Generation of new databases is highly dependent upon the potential value of the forensic tool. The entire issue of reference data and the means by which it can be shared is a possible topic for future consideration by the ITWG.

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